Hydrology, biogeochemistry, and plant community development in a created river diversion oxbow wetland in the Ohio River basin, USA

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Introduction

The National Academy of Sciences has called for the creation and restoration of 4 million ha of wetlands in the United States by 2010. Mitsch et al. (2001, 2005a) and Mitsch and Day (2006) have suggested that the restoration of 2 million ha of wetlands is necessary in the Mississippi river basin alone to mitigate the hypoxic zone in downstream coastal waters of the Gulf of Mexico. One of the ideal locations for many of these wetlands is near rivers where river waters can be diverted mechanically or naturally into the wetlands. Riparian wetlands have the advantage of being connected to systems that routinely provide river water and propagules; advantages of the wetlands to the riverine system include the provision of complementary still-water habitat that serves as a nursery for fish and other aquatic life, improvement of water quality and flood storage during river flood events.

River diversion wetlands are wetlands fed primarily by flooding streams, which allows for seasonal floodwaters to deposit sediments and chemicals into the wetlands and for the water to then seep back into the stream (Mitsch and Day, 2006). Because there are both artificial and natural levees along major sections of streams, it is often possible to create such wetlands with minimal construction work, by removing portions of levees to allow floodwater to enter the wetlands. The wetland could be designed to capture floodwater and sediments and slowly release the water back to the river after the flood passes. This is the design of natural riparian wetlands in bottomland hardwood forests (Mitsch and Day, 2006).

As river diversions become an increasingly popular tool for the ecological engineering of wetlands in downstream portions of watersheds (e.g., Reyes et al., 2000) it is important to evaluate this approach in upper watersheds to determine if this is an appropriate tool to use at both ends of large catchments. Furthermore, if watershed analysis is to be attempted (Reyes et al., 2000), we must have good data that detail how specific sites and wetland designs function. Some studies have compared wetlands in upper and lower portions of large watersheds (e.g., Mitsch et al. 2005a), but more study is needed regarding what function(s) specific river diversion designs provide in various climates.

There has been a great deal of research on how riparian wetlands function (Mitsch and Gosselink, 2000) and on the relative success of specific wetland restoration and creation projects (Mitsch and Wilson, 1996; Zedler and Callaway, 2000; Cole and Schafer, 2002). However, little research has been conducted in regards to the specific design features that lead to optimal functioning of created and restored river diversion wetlands. Also, while many studies have determined the overall efficacy of wetlands, few have analyzed these ecosystems in enough detail to determine which parts of the wetland are performing which functions. In addition, most studies do not explicitly take into account rare but important hydrologic events such as spring floods and rainstorms. At these times the nutrient retaining functions of a wetland can be greatly diminished (Raisen, 1995; Raisen et al., 1997), primarily due to reduced retention time. Some studies have showed that certain designs of created wetlands can compromise retention ability (Wong and Somes, 1995; Fink and Mitsch, 2004). The use of percent cover of vegetation is a poor indicator of overall wetland function (Reinartz and Warne, 1993). A critical need exists for detailed analyses of the structure and function of created wetlands.

The importance of river flood events is increasingly recognized in the field of restoration ecology and attempts have been made to reconnect rivers with their natural floodplains (Day et al., 1995; Galat et al., 1998; Hensel et al., 1998; Molles et al., 1998; Toth et al., 1998; Henry et al., 2002; Mitsch and Day, 2006). In addition to the water quality merits of river diversion wetlands, increasing the connectivity between rivers and floodplains can have a marked impact upon floral and faunal communities. The succession of herbaceous wet-meadow wetlands to wooded wetland (or wooded upland) has been well documented (Keddy and Reznicek, 1986; Nilsson, 1984). One potential benefit of river diversion wetlands with fluctuating water levels is to create/restore a mixed habitat of wooded and herbaceous wetland (Toner and Keddy, 1997).

Hydrologic conditions directly affect chemical and physical processes governing nutrient and suspended solids dynamics within wetlands (Mitsch and Gosselink, 2000). The rate at which a wetland's water quality changes is generally acknowledged to be dependant on nutrient concentrations in the inflow, the chemical form of the nutrient in question, and water flux (Knight et al. 1987). For example, maximum efficiency of nitrogen removal occurs at loading rates below 10 g-N m^{-2} yr^{-1} (Lane et al., 2003; Spieles and Mitsch, 2000), when diverted water is spread out over the largest possible wetland area (Lane et al., 1999; Blahnik and Day, 2000), and when the NH3:

NO3- ratio is less than 1.0 (Boustany et al., 1997). Because water is unevenly distributed in flow-through wetlands due to different degrees of channelization, microtopography, animal activity, and patterns of vegetative growth (Kadlec 1994), different parts of a diversion wetland will function differently.

The objective of this project was to determine the effectiveness of a created river diversion wetland in the upper Ohio River basin at developing into a viable, multifaceted ecosystem. We focused specifically on water quality functions and the development of herbaceous plant communities in this riparian wetland.

Methods

Site Description

The wetland examined in this study is located at the Olentangy River Wetland Research Park at The Ohio State University in Columbus, Ohio, USA. Water enters the oxbow through a Red Field TideflexTM check valve when the river elevation is higher than the wetland, and flows back to the Olentangy River though an outflow control weir by gravity. The wetland has two significant vegetation zones. The northern half (closest to the inflow) is an emergent marsh, and the southern half (closest to the outflow) is an open water basin. Lack of vegetation in the southern half is primarily due to high water conditions during spring, which prevents germination of emergent aquatic plants outside of the littoral zone.

Vegetation survey

Vegetation and peak biomass surveys were conducted in August, 2003 and August, 2004. Sampling was carried out over meandering transects throughout the entire basin of the created oxbow, covering wet, transitional, and near-upland zones. For each plant species observed, relative abundance was estimated as present (0-5%), common (5-50%), or abundant (50-100%). Indicator status was determined using the Region I (Northeast) National Wetland Indicator List (Reed, 1998). Species not found on this list were recorded as non-listed (NL). Biomass was determined by establishing six transects across the oxbow that passed through the different elevation zones of the wetland. Three separate 1 m2 plots were selected at random along each transect, within areas supporting vegetation. In each plot, all above ground biomass was harvested, identified to species, and weighed. Sub-samples were dried in order to calculate wet-dry ratios. Aerial photographs (color film) taken in August 2004 were used to determine plant cover and ground-truth data were combined with the photo imagery to estimate the spatial extent of the different plant communities in the created oxbow.

Hydrology

The hydrology of the wetland was determined by measuring the water level of the created oxbow and the river with staff gauges, and by measuring the flow of water into and out of the wetland using a Swofer 2100 current meter and an ISCO 730 bubbler module. A simple mathematical model was developed to describe the inflow based on the elevation of the river relative to the oxbow water surface. Daily hydrologic budgets enabled calculation of loading and retention rates (by mass) of the various nutrients.

Water Quality

When the Olentangy River is at a sufficient stage (22.09 m above MSL) overflow occurs into the diversion wetland. Dawn and dusk inflow and outflow grab samples were taken between October 2002 and October 2004 during these flood events. Grab samples (n = 514 over the two water years) were analyzed for nitrate-nitrite, total Kjeldahl nitrogen, soluble reactive phosphorus (SRP), total phosphorus, and turbidity. Field measurements taken for dissolved oxygen (DO), temperature, conductivity, pH, and redox with a YSI 600XL data sonde. More detailed automatic sampling was conducted during some storm events using ISCO 6874 autosamplers at the inflow and outflow of the created oxbow. Samplers were set to hourly frequencies during high flow periods. This more detailed sampling strategy allowed a comparison of the wetland's functioning during high and low flow periods.

Nitrate/nitrite, soluble reactive phosphorous (SRP), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) used standard methods (APHA 1998, USEPA 1983) with a LACHET QuickChem FIA 8000 series autoanalyzer. Manual and auto-sampler samples were split into filtered (0.45 µm) and unfiltered subsamples, and analyzed for appropriate chemistries. (TP) and (SRP) were analyzed with an ascorbic acid and molybdate color reagent method. TP samples were digested by adding 0.5 ml of 5.6 N H2SO4 and 0.2 g (NH4)2S2O8 to 25 ml of sample and exposing the samples to a heated and pressurized environment in a chemical digester. TKN was determined using in-line persulfate digestion followed by the same cadmium reduction method used for nitrate determination. Suspended sediments were determined using an empirical correlation with turbidity (Harter and Mitsch, 2003). Turbidity was measured in the laboratory with using a Hach turbidimeter. Total nitrogen (TN) was estimated as the sum of TKN and nitrite/nitrate-N.

Results

Hydrology

From its creation in 1996 through 2004, the 3-ha created riparian wetland (referred to here as a created oxbow) received, on average, seven to eight natural flood pulses each year from the Olentangy River (Table 1). Inflow from 1998-2004 averaged 20 ± 4 m yr-1 (expressed as depth or m^3 m^{-2} yr^{-1}). The Olentangy River typically provides frequent, short (5-6 days of inflow) flood pulses into the created oxbow. These pulses typically result in 9-12 days of outflow from the wetland.

The created oxbow had distinct wet and dry seasons, particularly in 2004 (Figure 2). During the wet season (November-June) and the dry season (July-October) there were 165 and 7 days of inflow respectively. In 2003, the wet season was atypically dry and the dry season was atypically wet, with 53 days of flow in the wet season and 41 days of flow in the dry season. In 2003 and 2004 respectively, the oxbow received 21 m yr–1 and 27 m yr–1 of water through 17 and 8 independent flood pulses per yr, respectively (Table 1). The year 2004 was wet compared to most of the previous years of the wetland's existence (see previous data in Mitsch and Day, 2006). Despite differences between the frequency and magnitude of the flood pulses, the mean duration of flood pulse inflows and outflows were similar. In both years, inflow pulses were 5-6 days in duration and outflow pulses lasted 9-10 days (Table 1).

Vegetation

Of 105 species of plants identified in the created oxbow in 2003 and 2004 (Table 2), 55 were wetland indicator species (classified as FACW or OBL). The three macrophyte species contributing most to productivity were *Typha* sp., *Eleocharis* sp. and *Scirpus americanus* (Table 3), which together accounted for 68% of the macrophyte net primary productivity in the wetland. The dominant vegetation communities in the created oxbow were Typha sp., a woody fringe of *Salix* spp. and *Populus deltoides*, a mixed community of *Eleocharis* sp., *Juncus effusus*, and *Scirpus americanus*, and expanding patches of *Pontederia cordata* (Figure 2). While *Typha* sp. contributed most to the macrophyte productivity, its proportion of the productivity in the wetland decreased from 83% at the inflow to 0% at the outflow.

In May, 1997 the created oxbow was planted with 6900 rootstocks representing 21 species (*Cephalanthus occidentalis, Sagittaria latifolia, Equisetum* sp., *Zizania aquatica, Iris versicolor, Spartina pectinata, Lobelia cardinalis, Saururus cernuus, Juncus effusus, Asclepias incarnata, Pontederia cordata, Scirpus cyperinus, Sparganium eurycarpum, Alisma plantago-aquatica, Scirpus americanus, Scirpus fluviatilis, Acorus calamus, Potomogeton pectinatus, Polygonum* spp., and *Schoenoplectus tabernaemontani* (Mitsch et al., 1998). Seventy-five percent of these species still persist in the wetland. However, only two of the original planted species, *Scirpus americanus* and *Juncus effusus*, make up a significant portion of the 2003-04 wetland primary productivity.

Nutrients

There were significant differences (p = 0.05) in the quality of the river water entering the oxbow between the two sampling years (Table 4). In 2003, the concentration of SRP in the influent was half of the level in 2004. In contrast, concentrations of TP and NO_3^--NO_2^- were twice as high in 2004 compared to 2003. Total Suspended Solids (TSS) were also higher in 2004 that in 2003.

Nutrients and sediments decreased through the created oxbow for all parameters examined (Figure 3), with the exception of TKN, which increased through the wetland. There were significant differences between years in percent removal of nutrients by concentration, as the water passed through the oxbow (Table 4). In 2003, the reduction in the concentration of SRP was 11.8% higher than in 2004. The percent removal of TP was the same in both years despite the significant difference in the initial inflow concentration. NO_3^--NO_2^- decrease was 13.6% higher in 2004, even though there was a lower average inflow concentration that year. While TN decreased by 24% in 2004, its TKN fraction increased by 200% through the emergent marsh portion of the wetland, and then dropped across the open water portion for an overall increase in TKN of 25.6% in 2004, the only year in which it was measured.

In addition to longitudinal differences in water quality through the wetland, there were some significant differences in water quality laterally as well (Figure 3). In both 2003 and 2004 the concentration of SRP was significantly greater (nearly double) on the east bank than in the channel of the emergent marsh area. By the mid-point of the oxbow, the concentrations were numerically higher along the edges, but no longer significantly different from the channel. The pattern was similar for TP in 2004, but in 2003 there was no significant difference among concentrations in the channel vs. those along either shore, for TP or for NO_3^--NO_2^-. Concentrations of TKN were significantly higher along the east bank, especially near the end of the emergent marsh area, and significantly lower along the west bank of the oxbow in the emergent zone and at the midpoint. In the open water area, both edges were numerically higher than the channel, but this difference was not significant.

Table 1. Frequency and duration of flood pulses in a created oxbow wetland on the Olentangy River in central Ohio, USA.

	Pulses per year	Mean duration of pulses, days	
		Inflow	Outflow
1996-2002	7-8	5-6	12
2003	17	5-6	10
2004	8	5-6	9

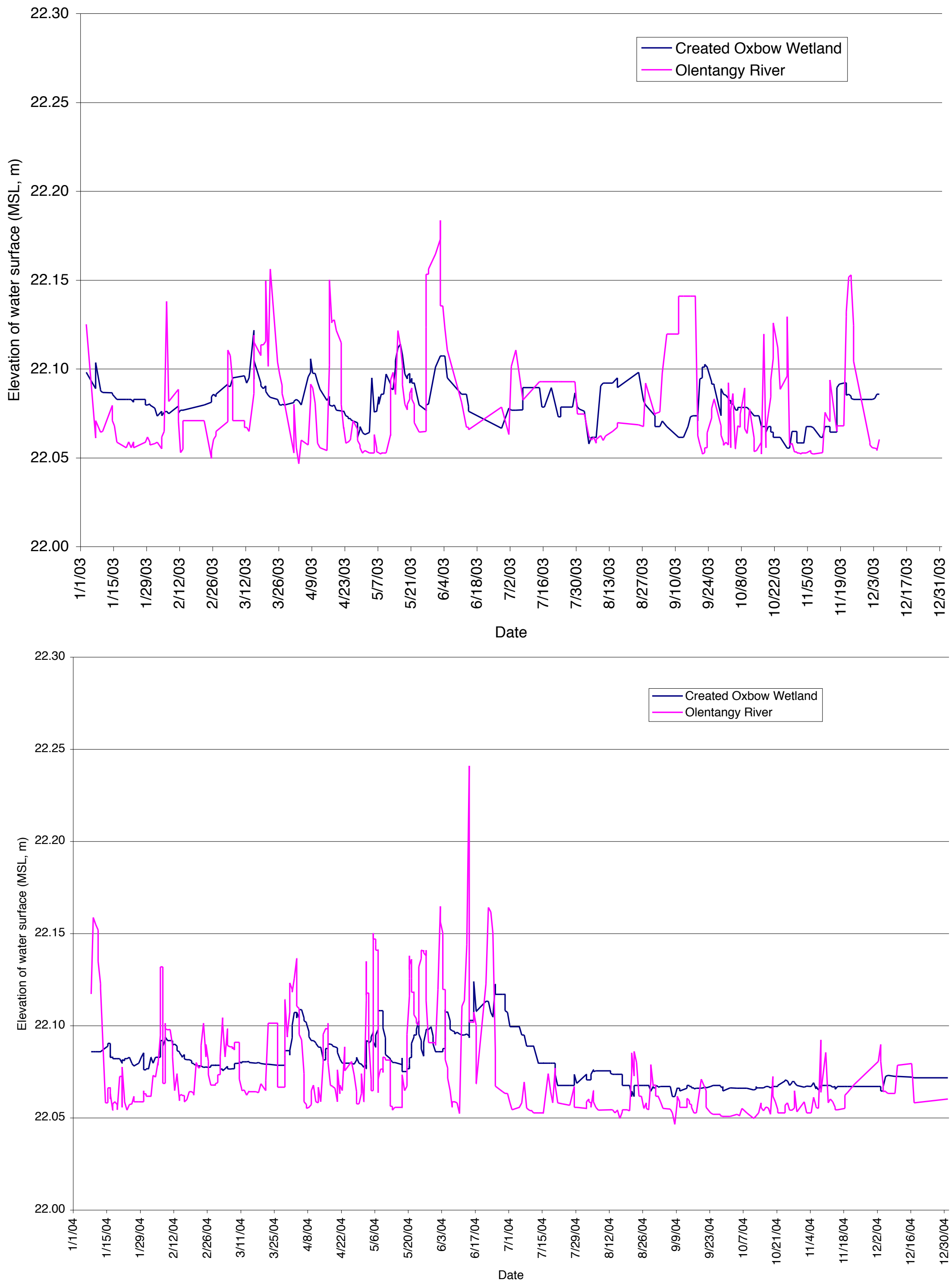

Figure 1. Daily hydrograph for a created diversion oxbow wetland in central Ohio, USA. In 2003, the top graph, there were several flood events during the late summer, which in a typical year is the dry season in this region. In 2004, the lower graph, the pattern is more typical with almost no flow events during the dry season.

Table 2. Total plant list in the created oxbow during ground surveys conducted in August 2003 and 2004. Relative abundance: P = present; C = common; A = abundant. Indicator status: OBL = obligate, FACW = facultative wetland, FAC = facultative, FACU = facultative upland, UPL = upland, NL = not listed. Most of the diversity was provided by species located on the banks of the wetland, above the regularly flooded waterline and outside of the range of most of biomass transects.

Scientific Name	Common Name	Relative Abundance	Indicator Status
Abutilon theophrasti	Velvet leaf	P	NL
Acer negundo	Boxelder	P	FACW
Acer rubrum	Red maple	P	FAC
Alisma plantago-aquatica	Water plantain	P	OBL
Ambrosia artemissiifolia	Common ragweed	P	FACU
Andropogon geradii	Big bluestem	P	FAC
Apocynumn cannabinum	Indian hemp	P	FACU
Arctius minius	Burdock	P	NL
Asclepias tuberosa	Swamp milkweed	P-C	OBL
Aster sp.	Aster	P	FAC
Baptisia lacteal	White wild indigo	P	FACU
Bidens cernua	Nodding beggars tick	P	OBL
Bidens comosa	Leafy-bract beggars tick	P	FACW
Bidens frondosa	Devil's beggars tick	P	FACW
Bidens laevis	Brook sunflower	P	OBL
Bouteloua curtipendula	Side oats grama	P	NL
Bromus ciliatus	Brome grass	P	FACW
Calystegia sepium	Hedge bindweed	P	NL
Carex frankii	Frank's sedge	P	OBL
Carex lurida	Shallow sedge	P	OBL
Carex vulpinoidea	Fox sedge	P	OBL
Cassia fasciculate	Partridge pea	P	FACU
Cephalanthis occidentalis	Button bush	P	OBL
Cirsium arvense	Canada horseweed	P	FACU
Cornus sp.	Dogwood	P	N/A
Crataegus sp.	Hawthorn	P	N/A
Cyperus sp.	Flat sedge	P	N/A
Cyperus strigosis	Straw-color flat sedge	P	FACW
Daucus carota	Queen Anne's Lace	P	NL
Desmanthis illinoensis	Prairie bundle flower	P	FAC
Desmodium canescens	Horay tick-trefoil	P	FAC
Diodia teres	Buttonweed	P	UPL
Dipsacus sylvestris	Teasel	P	NL
Echinochloa crusgalli	Barnyard grass	P-C	FACW
Eleocharis acicularis	Least spike rush	C-A	OBL
Eleocharis obtuse	Blunt spike rush	P	OBL
Eleocharis sp.	Spike rush	P	N/A
Elymus canadensis	Nodding wild rye	P	FACU
Erigeron canadensis	Horseweed	P	NL
Eupatorium perfoliatum	Common boneset	P	FACW
Glyceria striata	Fowl meadow grass	P	OBL
Helenium autumnale	Common sneezeweed	P-C	FACW
Hibiscus moscheutos	Swamp rose mallow	P	OBL
Iris versicolor	Northern blueflag	P	OBL
Juncus canadensis	Canada rush	P	OBL
Juncus effusius	Soft rush	P-C	FACW
Juncus torreyi	Torrey's rush	P	FACW
Juncus vaseyi	Vasey's rush	P	FACW
Leersia oryzoides	Rice cut-grass	C	OBL
Liatris spicata	Blazing star	P	FAC
Lindernia dubia	False pimpernel	P	OBL
Lobelia cardinalis	Cardinal flower	P	FACW

Lobelia sp.	Lobelia	P	N/A
Ludwigia palustris	Marsh seedbox	P	OBL
Lycopus americanus	American bungleweed	P	OBL
Lythrium salicaria	Hyssop loosestrife	P	OBL
Melilotus officinalis	Yellow sweet clover	P	FACU
Mentha arvensis	Field mint	P	FACW
Mimulus alatus	sh. wing monkey flower	P	OBL
Mimulus ringens	Monkey flower	P	OBL
Oenothera biennis	Evening primrose	P	FACU
Panicum virgatum	Switchgrass	P	FAC
Parthenocissus quinquiefolia	Virginia creeper	P	FACU
Penthorum sedoides	Ditch stonecrop	P	OBL
Phalaris arundinacea	Reed canary grass	P	FACW
Phleum pratense	Timothy grass	P	FACU
Phyla lanceolata	Frog's fruit	P	OBL
Plantago major	Common plantain	P	FACU
Plantanus occidentalis	Eastern sycamore	P	FACW
Poa compressa	Canada bluegrass	P	FACU
Polygonum hydropiper	Water pepper	P	OBL
Polygonum pensylvanicum	Pennsylvania smartweed	P	FACW
Polygonum persicaria	Lady's thumb smartweed	P	FACW
Pontedaria cordata	Pickeral weed	P-C	OBL
Populus deltoides	Cottonwood	P-C	FAC
Potamogeton pectinatus	Sago pondweed	P	OBL
Prunella vulgaris	Heal-all	P	FACU
Pycnantheum tenuifolium	Slender mountain mint	P	FACW
Rhus radicans	Poison ivy	P	NL
Rudbeckia hirta	Black-eyed Susan	P	FACU
Rudbeckia iancinata	Cut-leaf cloneflower	P	FACW
Rumec crispus	Curly dock	P	FACU
Sagittaria latifolia	Broad-leaf arrowhead	P	OBL
Salix alba	White willow	P	FACW
Salix exigua	Sandbar willow	P	NL
Salix nigra	Black willow	P	FACW
Schoenoplectus tabernaemontani	Soft stem bulrush	P	OBL
Scirpus americanus	Three-square rush	P-C	OBL
Scirpus cyperinus	Woolgrass	P	FACW
Scirpus fluviatilis	River bulrush	P	OBL
Setaria glauca	Yellow bristle grass	P	FAC
Setaria viridis	Foxtail	P	NL
Solanum carolinense	Horse nettle	P	FACU
Solidago sp.	Goldenrod	P	N/A
Sorghum halepense	Johnson grass	P	FACU
Sparganiam eurycarpum	Giant bur-reed	P	OBL
Spartina pectinata	Prairie cord grass	P	OBL
Taraxacum oifficinale	Common dandelion	P	FACU
Trifolium hydridum	Alsike clover	P	FACU
Trifolium pratense	Red clover	P	FACU
Typha sp.	Cattail	A	N/A
Verbena hastate	Blue vervain	P	OBL
Vernonia gigantean	Tall ironweed	P	FACW
Vitis vulpina	Wild grape	P	FAC
Xanthium strumarium	Rough cocklebur	P-C	FAC

Table 3. Estimated aboveground net primary productivity, based on peak biomass, in the created oxbow in 2004 for the 11 most dominant emergent macrophytes.

Species	NPP (g m-2 yr-1)	% of total
Typha sp.	276	28.0
Leersia oryzoides	66	6.7
Juncus effusus	140	14.2
Verbesnia alterniflora	35	3.5
Pontederia cordata	2	0.2
Scirpus americanus	191	19.4
Eloocharis sp.	209	21.2
Phragmites australis	26	2.7
Mixed FACW veg	23	2.3
Sparganium eurycarpum	16	1.6
Juncus canadensis	2	0.2
Total	986	100

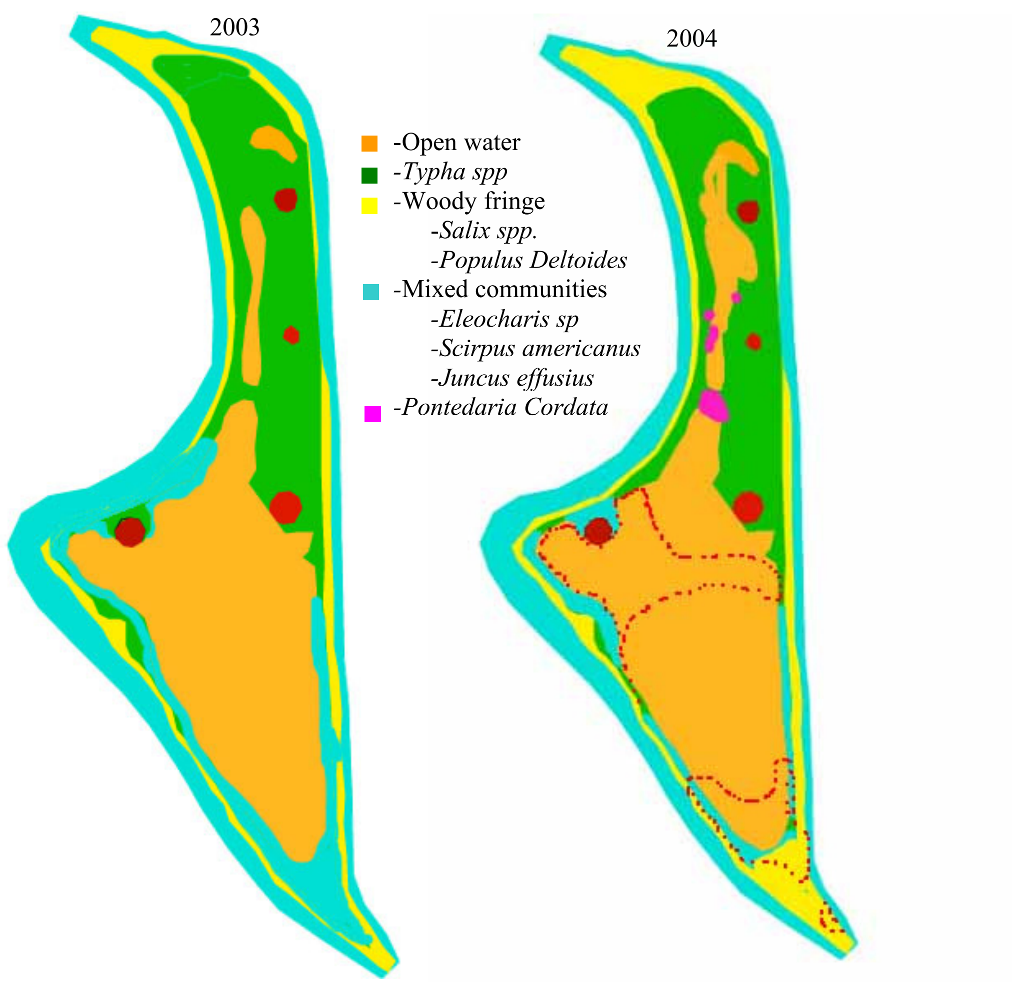

Figure 2. Dominant vegetation communities in the created oxbow wetland in 2003 and 2004. The area in the 2004 map marked with the dotted lines shows the extent of the spread *Xanthium strumarium* following a prolonged drawdown and after vegetation and productivity surveys in this study.

Table 4. Mean nutrient concentrations and turbidity [SRP = soluble reactive phosphorus, TP = total phosphorus, NO3- + NO2- = nitrate and nitrite, TN = total nitrogen, and TSS = total suspended solids] in the oxbow wetland created at the Olentangy River Wetland Research Park, 2003-2004, when flooded river water is flowing through the wetland. TN = TKN + NO3- + NO2- = (as N).

Parameter	Year	Inflow	Mid-point	Outflow	% Removal
SRP (µg-P L^{-1})	2003	60±1 (79)[b]	13±1 (16)[bc]	27±1 (97)[c]	55.3
	2004	33±1 (62)[b]	36±8 (6)[b]	19.0±0.3 (87)[c]	43.5
TP (µg-P L^{-1})	2003	92±6 (8)[b]	77±5 (7)[bc]	68±5 (6)[b]	25.7
	2004	203±2 (77)[b]	144±11 (7)[bc]	150±1 (102)[b]	26.3
NO_3^- + NO_2^-(mg-N L^{-1})	2003	4.40±0.04 (58)[b]	2.32±0.14 (14)[bc]	2.65±0.02 (79)[b]	39.9[b]
	2004	1.81±0.01 (83)	0.66±0.07 (7)[bc]	0.77±0.01 (120)[b]	57.3[b]
TN (mg-N L^{-1})	2003	-	-	-	-
	2004	3.04±0.05 (77)	3.17±0.35 (7)[c]	2.31±0.02 (102)[c]	24.0
TSS (mg L^{-1})	2003	14.9±1.1 (79)[b]	14.2±1.9 (16)[b]	9.1±0.4 (99)[bc]	38.9[b]
	2004	19.5±0.9 (87)[b]	14.6±2.9 (7)[bc]	16.4±0.4 (128)[b]	15.9[b]

Mean ± Standard Error (number of samples)
[b]Significant difference between years (p = 0.05)
[c]Significant difference from upstream location (p = 0.05)

For turbidity, the only significant lateral difference was in the open water basin, where both edges were significantly less turbid than the channel.

Discussion

Vegetation Dynamics in a Diversion Wetland

In the seven years since the oxbow was created, the range of the Typha dominated community has not expanded beyond the upper third of the wetland. This is due to a combination of factors. The first is the significant reduction of available nutrients in the wetland. By the end of the emergent marsh, nitrate-nitrite concentrations have been reduced to low levels, allowing other plants to better compete with Typha. Second, water levels during spring vegetation emergence are typically quite deep in the lower two-thirds of the oxbow, and deep water is not favorable for Typha growth or germination. Third, there is a long unobstructed fetch on the two-thirds of the wetland. It is possible that the *Typha* community stops where it does more as a result of wind and subsequent wave action than as a result of the nutrient concentrations or water depth. This question will be better answered as trees on the southwest bank continue to mature and form a more significant windbreak.

Woody species have encroached across the outflow swale of the wetland. This may eventually cause the sediment surface of the outflow to rise, reducing outflow and causing a "ponding" effect in the southern basin of the created oxbow. If ponding does occur, the wetland will have open water habitat even in drier years, and the mudflat will not appear until later in the summer. The mudflat may not be exposed at all in years such as 2003, where there are significant summer storm-driven flooding events.

The changing water coverage in the southern basin of the created oxbow affected the extent of *Xanthium strymarium*. As water receded in the late summer (after the vegetation surveys and biomass measurements were taken) *Xanthium strymarium* rapidly colonized the exposed mudflat, and was the dominant species on the mudflat until the onset of the first heavy frost.

Water Quality Dynamics

The difference in mean concentration of total phosphorus between 2003 and 2004 is likely the result of a greater percentage of the total samples in 2003 coming from the dry season than in 2004. The difference in number of samples taken occurred because there was more rain, and thus more flooding, in summer, 2003 than in 2004. The difference in the timing and amount of flooding does not necessarily explain the difference in influent nitrate-nitrite levels, which have been measured to can fluctuate dramatically from year to year in the Olentangy River.

The increase in turbidity in the open water portion of the oxbow in 2004 coincided with an increased number of common carp (*Cyprinus carpio*) in the wetland. Carp swam up the outflow of the oxbow during a large flood pulse from the river in late spring, and took up residence in the wetland.

Fluctuations in total nitrogen are only partially explained by the NO3- fraction. Much of the fluctuation is explained by changes in the TKN concentration. The increase and subsequent decrease in the TKN concentration matches vegetation patterns observed in the created oxbow. TKN steadily increases through the emergent marsh portion of the wetland, and then decreases across the open water section. Ammonium concentrations within the wetland usually negligible (< 0.05 mg L-1); therefore it is likely that the emergent marsh area contributes organic nitrogen to the water column. The higher concentration of TKN along the east bank also fits this pattern. Emergent biomass is denser along this bank than it is along the central channel and the west bank of the oxbow.

Ninety-two percent of the nitrate-nitrite loss occurs in the emergent marsh in the upper third of the oxbow. This indicates that either the concentration of nitrate-nitrite is too

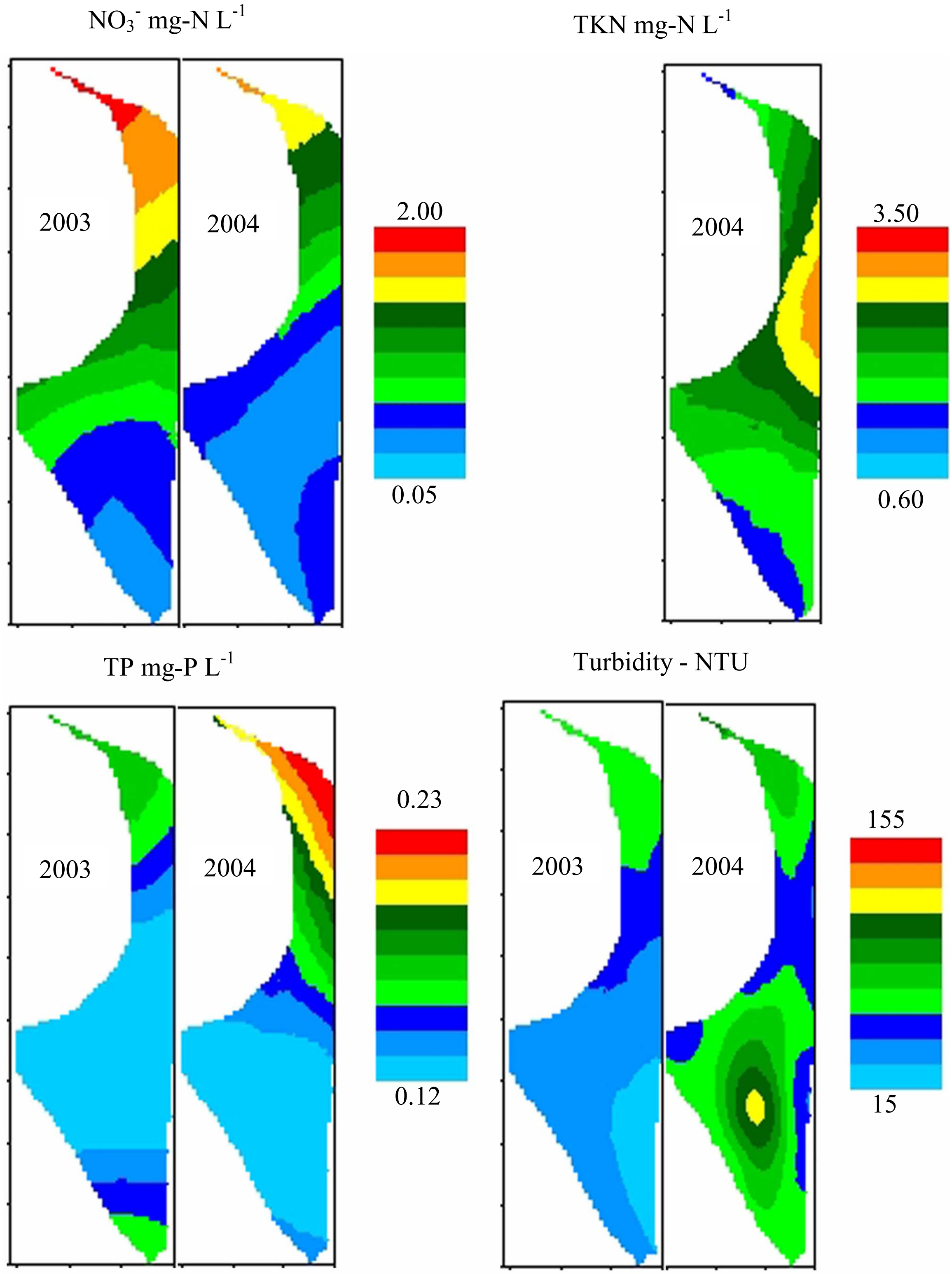

Figure 3. Kriging diagrams of the nitrate+nitrate, total Kjeldahl nitrogen, total phosphorus, and total suspended solids in a created diversion oxbow wetland in central Ohio in 2003 and in 2004.

low to be further reduced by wetland processes or that the lack of emergent vegetation in open water areas results in an environment that is not conducive to denitrifying bacteria. The environment may be less suitable because the open water area has fewer plant roots or other plant tissues, and subsequently less organic matter on the benthic substrate for denitrifying bacteria to use as a carbon source. This explanation may also account for the differences between the nitrate concentration in the central channel and the edges of the wetland, as the emergent biomass is significantly greater at the edges. The increase and decrease in TKN and nitrate-nitrite appear to be dependent on inverse conditions. The portions of the wetland that show the greatest decrease in NO_3^- are the areas with the greatest increase in TKN.

There was consistently a greater concentration of TP and SRP along the east bank than along the west bank. Phosphorus can be released from dried soils rich with sorbed phosphorus, when these soils are inundated (Olilia et al., 1997). Therefore it is likely that higher concentrations of phosphorus in the edge zones were a result of the wetland area expanding and contracting as the oxbow received and discharged water during and following pulses.

Nutrient Loading and Retention Rates

Loading and retention rates of the various nutrients were variable throughout 2004 (Table 5). The total loading rate in 2004 for nitrate-nitrogen, total nitrogen, soluble reactive phosphorus, and total phosphorus were 32.2 g-N m^{-2} yr^{-1}, 64.5 g-N m^{-2} yr^{-1}, 0.48 g-P m^{-2} yr^{-1}, and 6.1 g-P m^{-2} yr^{-1} respectively. Retention rates were 15.4 g-N m^{-2} yr^{-1}, 32.3 g-N m^{-2} yr^{-1}, 0.05 g-P m^{-2} yr^{-1}, and 4.48 g-P m^{-2} yr^{-1} respectively for the same nutrients. The rates of nitrate-nitrogen and total phosphorus retention are within the ranges of 10-40 g-N m^{-2} yr^{-1} and 0.5 - 5 g-P m^{-2} yr^{-1} reported by Mitsch et al. (2000). The nitrate-nitrogen rate is at the low end of the range predicted by that paper while the phosphorus retention is at the high end. Long-term experience with the adjacent experimental wetlands at this same Ohio location (Mitsch et al., 2005b) suggest that nitrate-nitrogen retention increases or remains steady with time while total phosphorus retention appears to decrease with time.

During the eight discrete flood pulses, mean loading rates were 0.97 g-N m^{-2} per pulse, 2.54 g-N m^{-2} per pulse, 0.036 g-P m^{-2} per pulse, and 0.27 g-P m^{-2} per pulse respectively. Retention rates during the eight flood pulses were 0.71 g-N m^{-2} per pulse, 0.92 g-N m^{-2} per pulse, 0.016 g-P m^{-2} per pulse, and 0.08 g-P m^{-2} per pulse respectively (Table 5). Overall, there was a 74%, 41%, 46%, and 31% reduction in the mass of N-NO_3^-, TN, P-SRP, and TP respectively throughout the entire year during eight pulses. Sometimes the oxbow would receive a flood from the river that was not of sufficient magnitude to create outflow, or outflow would occur solely as a result of precipitation. These two "incomplete pulse" scenarios are not included in the "during pulse" calculations but they are incorporated in the total annual loading calculation. Also, the "during pulse" calculations are based only on the actual days of flow, whereas the annual calculations are not. Retention rates for TN, SRP, and TP were all higher early in the year, before the start of the growing season.

Loading rates were variable not only between flood pulses, but also within flood pulse as shown in flood data from February 2004 (Figure 4). Peaks in the loading rate do not necessarily match with the moments of greatest nutrient concentration in the influent or the moments of greatest hydraulic flow. There was no significant correlation for either situation (r = 0.25 and r = 0.36, respectively).

Table 5. Annual mean loading and retention of nitrate-nitrite (NO_3^-), total nitrogen (TN), soluble reactive phosphorus (SRP), and total phosphorus (TP) during 2004 in the river diversion oxbow (ave ± std. error). Rates are in g-N m^{-2} yr^{-1} or g-P m^{-2} yr^{-1} as is appropriate. The mean loading rate, export rate, and the retention rate of the nutrients during the eight flood pulses in the mitigation oxbow wetland in 2004 are also shown. Rates and the mass retention are calculated according to the number of actual days of flow; note that the duration of the inflow and outflow are different.

		NO3--N	TN	SRP	TP
Yearly Mean					
Loading Rate	g-X m^{-2} yr^{-1}	32.2±0.2	64.5±0.4	0.48±0.00	6.10±0.04
Export Rate	g-X m^{-2} yr^{-1}	16.8±0.2	32.2±0.3	0.43±0.01	1.62±0.01
Retention Rate	g-X m^{-2} yr^{-1}	15.4±0.2	32.3±0.2	0.05±0.01	4.48±0.03
Percent Mass		48±3	50±4	10±1.0	73±8.0
During Eight Pulses					
Loading Rate	g-X m-^{2} $pulse^{-1}$	0.97±0.11	2.54±0.47	0.036±0.006	0.27±0.07
Export Rate	g-X m^{-2} pulse-^{1}	0.25±0.01	1.34±0.03	0.019±0.004	0.19±0.06
Retention Rate	g-X m^{-2} $pulse^{-1}$	0.71±0.10	0.92±0.44	0.016±0.003	0.08±0.01
Percent (by mass)		73.9±11.1	40.6±6.8	46.8±24.9	31.1±6.1

Unit 'X' is N or P, as appropriate

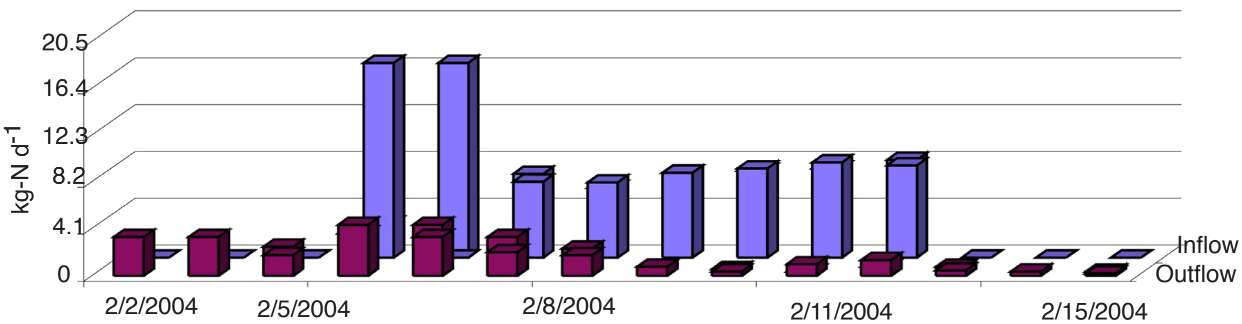

Figure 4 Nitrate loading and export (as kg N/d) during the second major flood event of 2004. The flood event occured February 3-15, 2004.

Conclusions

The created oxbow wetland has developed a diverse and reasonable assemblage of emergent macrophytes. The wetland is dominated by Typha sp. in the emergent marsh area, whereas there is more plant diversity in the southern section where nutrients are lower in concentrations. Frequent fluctuations in the water level in the southern section during spring flood events, and the drying out of the southern section into a large mudflat during late summer account for many of the differences between the two halves of the wetland.

The created oxbow is an effective nutrient sink, especially during the initial mid-winter snowmelt that is common in this part of Ohio. Nitrate-nitrogen retention was dependent upon several hydrologic factors including loading rate, water depth, and hydraulic retention time. As a result, the wetland had a reduced capacity to attenuate nitrogen during periods of high flow in the dry season, compared to the wet season flows. Phosphorus decreased through the created oxbow, and concentration of phosphorus varied significantly in the different zones of the wetland during different seasons, likely as a result of changes in hydrology and morphology across seasons. Over the course of a year the wetland was a net sink for phosphorus. During early spring high flow periods, the wetland retained phosphorus, but it was a source of phosphorus during large thunderstorm events in the drier summer months. The created oxbow's reduced ability to retain phosphorus during "dry season" flood pulses suggests that the wetland either reaches it's assimilative capacity early in the year, or that the lower water levels and increased carp population combined to produce conditions conducive to the export of suspended solids and phosphorus.

Overall, the mitigated oxbow design has shown itself to be a success in ecological terms. It would be worth replicating this wetland design in other locations to examine how it functions under a variety of climatic and hydrological conditions.

References

Blahnik, T., J.W. Day. 2000. The effects of varied hydraulic and nutrient loading rates on water quality and hydrologic distributions in a natural forested treatment wetland. Wetlands 20: 48-61.

Boustany, R.G., C.R. Crozier, J.M. Rybczyk, and R.R. Twilley. 1997. Dennitrification in a south Louisiana wetland forest receiving treated sewage effluent. Wetland Ecology and Management. 4: 273-283.

Cole, C.A. and D. Schafer. 2002. Section 404 wetland mitigation and permit success criteria in Pennsylvania, USA, 1986-1999. Environmental Management. 30:508-515.

Day J.W., Madden C.J., Twilley R.R., Shaw R.F., McKee B.A.,, Dagg M.J. et al. 1995. The influence of Atchafalaya River discharge on Fourleague Bay, Louisiana (USA). In: Dyer K.R. Orth R.J. (eds), Changes in Fluxes in Estuaries. Olsen and Olsen, New York, pp. 151–160.

Fink, D.F. and W.J. Mitsch. 2004 Seasonal and storm event nutrient removal by a created wetland in an agricultural watershed. Ecological Engineering. 23:313-325.

Galat D.L., Frederickson L.H., Humburg D.D., Bataille K.J., Bodie J.R., Dohrenwend J. et al. 1998. Flooding to restore connectivity of regulated, large-river wetlands. (Lower Missouri River). Bio-Science 48: 721–733. Hammer, D. E. and R. H. Kadlec. 1986. A model for wetland surface-water dynamics. Water Resources Research 22:1951–1958.

Harter, S.K. and W.J. Mitsch. 2003. Patterns of short-term sedimentation in a freshwater created marsh. Journal of Environmental Quality. 32(1):325-334.

Henry, C.P., C. Amoros, N. Roset. 2002. Restoration ecology of riverine wetlands: A 5-year post-operation survey on the Rhône River, France. Ecological Engineering. 18(5):543-554.

Hensel P.F., Day J.W., Pont D. and Day J.N. 1998. Short-term sedimentation dynamics in the Rhone River Delta, France: the importance of riverine pulsing. Estuaries 2:52–65.

Kadlec, R. H. 1994. Detention and mixing in free water wetlands. Ecological Engineering 3:1–36.

Keddy, P. A., and A. A Reznicek. 1986. Great Lakes vegetation dynamics: the role of fluctuating water levels and buried seeds. Journal of Great Lakes Research 12:25–36.

Knight, R. L., T. W. McKim, and H. R. Kohl, 1987. Performance of a natural wetland treatment system for wastewater management. Journal of the Water Pollution Control Federation 59:746–754.Lane, R.R., H.S. Mashriqui, G.P. Kemp, J.W. Day, J.N. Day, A. Hamilton. 2003. Potential nitrate removal from a river diversion into a Mississippi delta forested wetland. Ecological Engineering. 20: 237-249.

Lane, R.R., H.S. Mashriqui, G.P. Kemp, J.W. Day, J.N. Day, A. Hamilton. 2003. Potential nitrate removal from a river diversion into a Mississippi delta forested wetland. Ecological Engineering 20: 237-249.

Lane, R.R., J.W. Day, B. Thibodeaux, 1999. Water quality analysis of a freshwater diversion at Caernarvon, Louisiana. Estuaries 22, 327–336.

Mitsch, W.J., S. Johnson, and M. Liptak. 1998. Planting and planting success of the new mitigation wetland at the Olentangy River Wetland Research Park in 1997. In: Mitsch, W.J. and V. Bouchard, eds. Olentangy River Wetland Research Park Annual Report 1997, Ohio State University, Columbus. pp. 205-210.

Mitsch, W.J and J.G. Gosselink. 2000. Wetlands, 3rd ed. John Wiley and Sons, New York.

Mitsch, W.J., A.J. Horne, and R.W. Nairn. 2000. Nitrogen and phosphorus retention in wetlands —Ecological approaches to solving excess nutrient problems. Ecological Engineering 14: 1-7.

Mitsch, W.J., J.W. Day, W. Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, N. Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: strategies to counter a persistent ecological problem. Bioscience. 51(5): 373-388.

Mitsch, W.J., J.W. Day, L. Zhang, R.R. Lane. 2005a. Nitrate-nitrogen retention in wetlands in the Mississippi River Basin. Ecological Engineering. 24:267-278.

Mitsch, W.J., L. Zhang, C.J. Anderson, A. Altor, and M. Hernandez. 2005b. Creating riverine wetlands: Ecological succession, nutrient retention, and pulsing effects. Ecological Engineering 25: 510-527.

Mitsch, W.J. and J.W. Day, Jr. 2006. Restoration of wetlands in the Mississippi-Ohio-Missouri (MOM) River Basin: Experience and needed research. Ecological Engineering in press

Molles M.C., Crawford C.S., Ellis L.M., Valett H.M. and Dahm C.N. 1998. Managed flooding for riparian ecosystem restoration. BioScience 48: 748–756.

Nilsson, C. 1984. Effect of stream regulation on riparian vegetation. Pages 93–106 in A. Lillehammer and S. J. Saltveit, editors. Regulated rivers. Universitetsforlaget A/S, Oslo, Norway.

Olila, O.G, K.R. Reddy, D.L. Stites. 1997. Influence of draining on soil phosphorus forms and distribution in a constructed wetland. Ecological Engineering. 14:107-126

Raisen, G.W. and D.S. Mitchel. 1995. The use of wetlands for the control of non-point source pollution. Water Science and Technology. 32:177-186.

Raisen, G.W., D.S. Mitchel, R.L. Croome. 1997. The effectiveness of a small constructed wetland in meliorating diffuse nutrient loadings from an Australian rural catchment. Ecological Engineering. 9:19-36.

Reed, P.B. Jr. 1998. Nation list of plant specie that occur in wetlands: Northeast (Region I). U.S. Fish and Wildlife Service, Washington, D.C., Biological Report 88 (26.1).

Reinartz, J.A. and E.L. Warne. 1993. Development of vegetation in small created wetlands in southeastern Wisconson. Wetlands 13:153-164.

Reyes E, M.L. White, J.F. Martin, G.P. Kemp, J.W. Day, A. Aravamuthan . 2000. Landscape modeling of coastal habitat change in the Mississippi Delta. Ecology 81: 2331–2349

Spieles, D.J. and W.J. Mitsch. 2000. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: a comparison of low- and high-nutrient riverine systems. Ecological Engineering. 14: 77-91.

Toner, M. and P. Keddy. 1997. River hydrology and riparian wetlands: a predictive model for ecological assembly. Ecological Applications. 7(1): 236-246.

Toth L.A., Melvin S.L., Arrington D.A. and Chamberlain J. 1998. Hydrologic manipulations of the channelized Kissimmee River. BioScience 48: 757–765.

Wong, T.H.F., Somes, N.L.G. 1995. A stochastic approach to designing wetlands for stormwater pollution control. Innovative technologies in urban stormwater. 145-151.

Zedler, J.B. and J.C. Callaway. 2000. Evaluating the progress of engineered tidal wetlands. Ecological Engineering. 15:211-225.